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Technical Research Note 207

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EFFECTS OF SPECTRUM SAMPLING ON SPEECH INTELLIGIBILITY

Anthony E. Castelnovo

COMBAT SYSTEMS RESEARCH DIVISION

U. S. Army
Behavioral Science Research Laboratory

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Anthony E. Castelnovo

James H. Banks, Jr., Task Leader

COMBAT SYSTEMS RESEARCH DIVISION
Aaron Hyman, Chief

U. S. ARMY BEHAVIORAL SCIENCE RESEARCH LABORATORY

Office, Chief of Research and Development
Department of the Army

Room 239, The Commonwealth Building
1320 Wilson Boulevard, Arlington, Virginia 22209

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FOREWORD

The MONITOR PERFORMANCE Work Unit employs controlled laboratory experimentation in developing and testing principles, techniques, and operating procedures to improve the performance of personnel working in a variety of Army monitoring jobs. The effects of factors associated with the signal, the monitoring task, the environment, and the individual in various combinations are studied simultaneously.

"Enhancement of Communication Operator Performance" is a work sub-unit concerned with variables affecting the intelligibility of audio signals and speech. Present emphasis is on the area of spectrum selection and binaural listening. The present publication reports on preliminary experimentation dealing with the effect on speech intelligibility of excising segments of the spectrum employed in a communication channel. The specific objective was to compare the effect of filtering out several narrow frequency bands located over the speech spectrum with that of eliminating a single band covering the same total extent.

The study was conducted as a part of RDT&E Project 2Q62106A723, "Human Performance in Military Systems," FY 1969 Work Program.

J. E. UHLANER, Director
U. S. Army Behavioral Science
Research Laboratory

EFFECTS OF SPECTRUM SAMPLING ON SPEECH INTELLIGIBILITY

BRIEF

Requirement:

To explore the effect on speech intelligibility of filtering out several narrow bands of frequencies from various parts of the speech spectrum as compared with excising the same total amount of the spectrum in a single band.

Procedure:

Phonetically balanced (PB) stimulus word lists spoken by three different individuals were presented to 36 subjects through a filter system which permitted variation in the configuration of pass bands over a 1300-cycle bandwidth. Experimental conditions totaled 54--18 filter configurations each under three noise conditions. Analysis of variance techniques were applied to the data.

Findings:

Intelligibility was significantly higher for configurations in which the bandwidths excised were distributed over the spectrum than for equal bandwidth concentrated in one area.

Findings held for all three noise conditions.

Utilization of Findings:

If these findings are confirmed for bandwidths covering a wider range of frequencies, voice radio communication could be facilitated in two ways: (1) Portions of the spectrum in which unwanted noise occurs could be filtered out, resulting in higher intelligibility of the message; and (2) greater use could be made of a given communication channel by sending more than one message over the channel at the same time, each message using different portions of the spectrum.

EFFECTS OF SPECTRUM SAMPLING ON SPEECH INTELLIGIBILITY

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EFFECTS OF SPECTRUM SAMPLING ON SPEECH INTELLIGIBILITY

OBJECTIVE

One of the more serious problems the operator in a military communication system faces is that of noise which obscures the message. The noise may be broad-band noise or appear in specific bands, depending on the source. If the noise appears in relatively narrow bands, these bands might be eliminated and with them, the unwanted noise. However, there are no firm data on which to estimate the effect on the operator's performance of such a procedure.

The present study was designed to gain preliminary information about the effect on performance of excising portions of the speech spectrum. It is recognized that sophisticated techniques, such as digital transmission of voice, are being developed and employed to overcome the effects of noise and to transmit communications in secure form. There are, however, instances where these techniques are not feasible, and where it may be useful to reduce the amount of spectrum dealt with by excising selected bands.

The frequency domain of speech and the relationship of frequency to intelligibility have been the subject of research by many investigators (1, 2, 3, 4, 5, 6). These investigators have measured average speech spectra and have studied the effects on speech intelligibility of excising continuous bands from the upper and lower areas of the speech spectrum; for the most part, these studies have involved filtering out a single portion, or pass band, of the spectrum. On the basis of results of these studies, communications equipment has been designed to take advantage of reduced spectrum requirements.

Another way of treating the frequency domain is to filter out pass bands from several locations in the speech spectrum simultaneously. Kryter employed a spectrum configuration in which two narrow bands were eliminated, a configuration which resulted in higher intelligibility than did elimination of a single band covering the same extent of the spectrum. In a follow-up study, Kryter (7) observed that for constant speech intelligibility the total effective bandwidth required for the best multiple pass-band system is less than that required for contiguous pass-band systems by a factor of 2. This phenomenon may be explained as a function of redundancy. Removing some narrow bands reduces redundancy but not necessarily intelligibility. That redundancy is a characteristic of the speech spectrum and that some reduction may be made without a corresponding reduction in intelligibility has been noted before. M. R. Schroeder (8) briefly reviewed the work of Homer Dudley, noting Dudley's contribution to the origin of Vocoders, which take advantage of the redundancy of the speech spectrum.

Apart from Kryter's work, which employed a limited amount of filtering, there appears to be no other relevant work in the literature. As for research on the effect of noise on a spectrum composed of discrete bands, there appears to be none at all. The present study concentrates on number and size of segments excised from the speech spectrum as they affect intelligibility and the effect of noise on the intelligibility of a speech spectrum composed of discrete bands. Such information would be useful in assessing the feasibility of eliminating segments of the spectrum which may carry particularly high levels of noise and for employing the spectrum space in the interstices for other uses.

METHOD

Spectrum Sampling

Sampling of the spectrum was accomplished by using a set of 24 electrical pass-band filters which permitted passing very narrow bands. The specifications for these filters are shown in Table 1. The bandwidths[1] of the individual filters at -16 dB varied from 50 Hz to 115 Hz. The 24 filters formed a 1300-cycle pass band from 373 Hz to 1684 Hz. Each of the 24 pass-band filters could be switched in and out of the circuit independently. The filter set was inserted in the system as shown in Figure 1. The system noise was -35 dB relative to the 200 root mean square (rms) value of the speech (integrated over .3 seconds).

Subjects

The stimulus material was presented to 36 test subjects. These were Army enlisted men under 30 years of age, with no language problem and no previous experience in the communication field. A hearing test conducted at the time of the experiment showed that all were in hearing category 1.

Stimulus Material

The speech material consisted of 18 phonetically balanced (PB) word lists (9) which had been recorded by three speakers, six lists by each speaker.

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[1] The bandwidth was computed for the -16 dB point to approximate the effective bandwidth of the filter. The -3 dB or -6 dB point often used in specifying the filter bandwidth does not take into account the intelligibility contributed by the filter skirt beyond that point.

Table 1

FILTER SPECIFICATIONS--FREQUENCY AS A FUNCTION OF LOSS IN dB

Filter	-30dB	-3dB	Center Frequency	-3dB	-30dB
1	364	379	398	415	434
2	402	415	436	449	466
3	438	450	470	484	499
4	469	483	505	519	538
5	504	519	533	557	579
6	545	560	583	597	618
7	583	598	624	644	666
8	627	644	668	688	714
9	674	690	712	734	755
10	718	734	755	779	802
11	763	779	813	827	850
12	813	330	840	877	901
13	860	878	904	927	955
14	913	928	941	976	1002
15	958	978	1010	1033	1056
16	1016	1033	1049	1087	1116
17	1066	1089	1123	1153	1182
18	1132	1153	1191	1216	1247
19	1196	1218	1257	1282	1293
20	1260	1283	1323	1352	1384
21	1330	1353	1370	1426	1458
22	1404	1426	1444	1500	1512
23	1472	1504	1540	1575	1614
24	1550	1579	1598	1662	1695

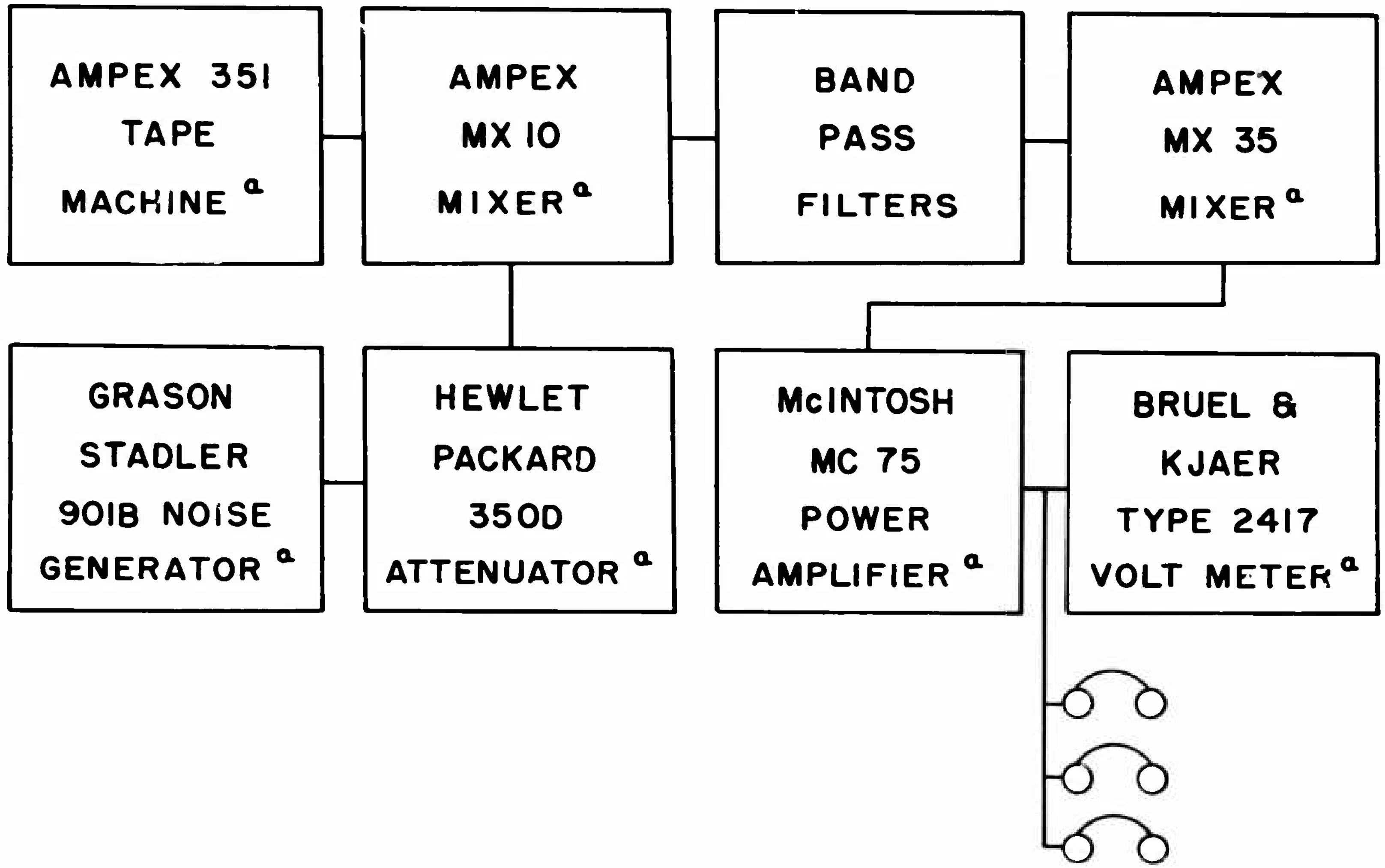

Figure 1. Block diagram of equipment used in experiment.

[a]Commercial names are used only for precision in describing the experimental procedure. Their use does not constitute indorsement by the Army or by BESRL.

Experimental Procedure

The subjects were located in an Industrial Acoustics Company series 1200 chamber[2] in which a very low level of ambient noise was maintained. PDR-10 headsets were employed.

The subjects were given 30 hours of training over a period of a week (6 hours a day for 5 days) in listening to PB word lists uttered by the three speakers. The materials had been subjected to filtering similar to that used in the experiment proper and mixed with noise.

Following the training, the subjects started the experimental sessions. These consisted of three half-hour sessions on each of three days. Each half-hour experimental session was followed by a one-hour rest period. Six experimental conditions were presented each experimental session. Thus, over the nine sessions, 54 experimental conditions were presented--18 filter conditions under each of 3 noise conditions. Figure 2 presents the filter conditions. The noise source was a Grason Stadler[2] noise generator set for "speech" shaping. Noise Condition 1 was zero noise from the noise generator; Noise Condition 2 was 25 dB below the maximum rms speech amplitude (integrated over .3 seconds). Noise Condition 3 mixed in noise at 15 dB below the maximum rms speech amplitude (integrated over .3 seconds).

Experimental Treatment

The design was such that all subjects, talkers, and word lists were associated with each of the experimental conditions. The subjects had been instructed to respond to each stimulus word regardless of how unsure they were; and except for rare instance, a response was made to each word.

The data were reduced to the mean intelligibility values for each of the 54 experimental conditions. Intelligibility was also computed by use of the Articulation Index, an objective measure based on [measured] pitch and other physical dimensions of the speech sound. An analysis of variance was made for the main effects and interactions of days, sets of experimental conditions, session, speaker, filter conditions, and noise conditions.

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[2] Commercial names are used only in the interest of precision in describing the experimental procedure. Their use does not constitute indorsement by the Army or by BESRL.

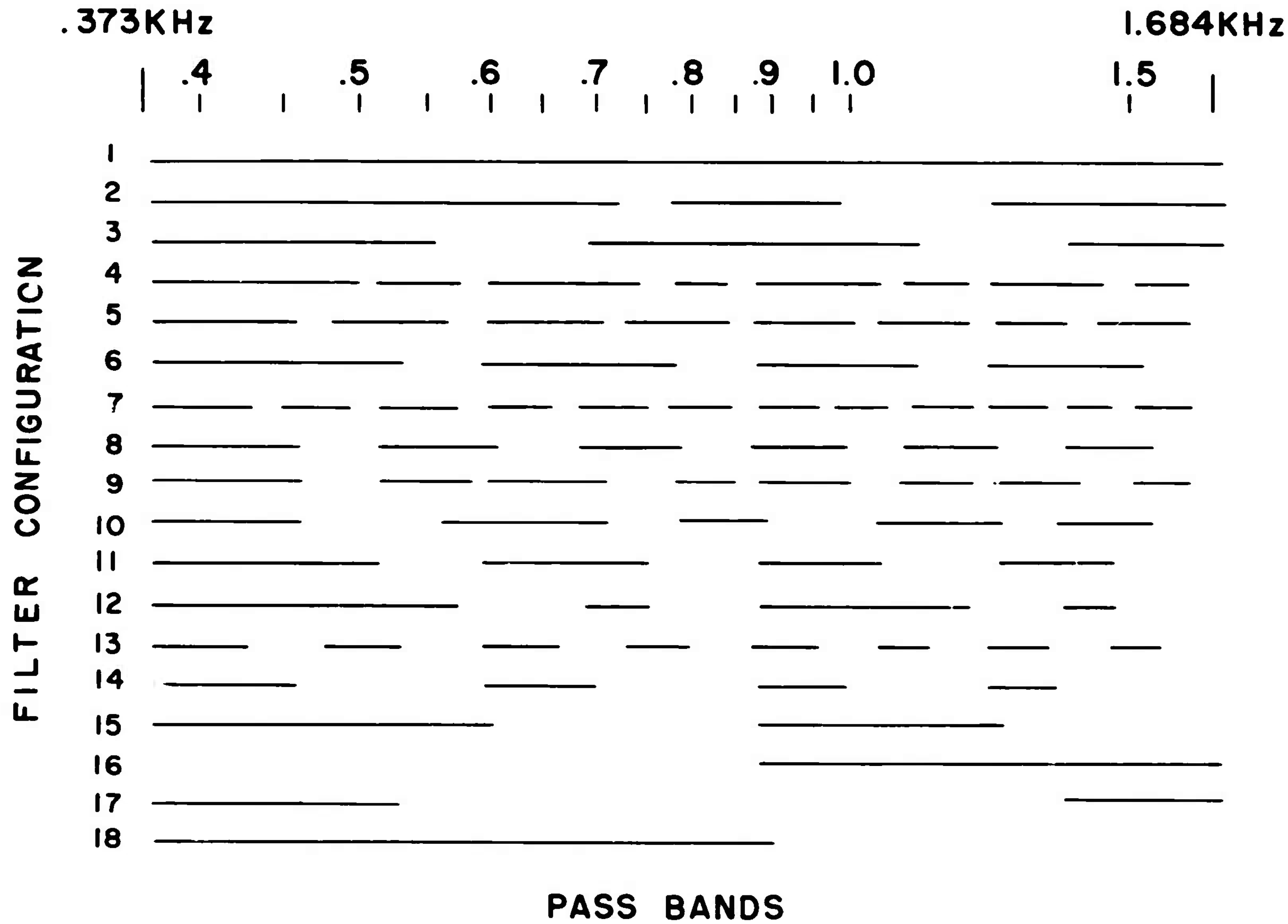

Figure 2. Pass bands of the 18 filter configurations, measured at the -16 dB point. (Gaps in the lines show the segments eliminated.)

RESULTS

Intelligibility values for the 18 filter configurations at the three noise levels are shown in Table 2 in comparison with the Articulation Index. Table 3 shows the analysis of variance results.

A slight significant improvement was found over the three days of testing even though the experimental sessions had been preceded by a week of training. This improvement, however, did not affect the results, as each of the 54 experimental conditions was replicated 12 times on each of the three days. As anticipated, the filter and noise factors were statistically significant beyond the .01 level. Blocks of experimental conditions, periods, and speakers produced non-significant F ratios, and the interactions of days by filter conditions and days by noise conditions showed a probability of occurrence between .10 and .05. The filter-by-noise level interaction was not significant, although there was a significant change in the relationship between bandwidth and intelligibility as a function of noise level, as discussed below.

Intelligibility produced by the different filter configurations was also compared to bandwidth and to the Articulation Index (Table 2). Each of the filter configurations used was fairly representative of the total 1300-cycle band. The filter configurations were designed to have the same average Articulation Index per cycle as the total spectrum in order to maintain a linear relationship between Articulation Index and bandwidth (Figure 3) and thus avoid confounding the variation in intelligibility emanating from two sources, amount of spectrum and use of spectra concentrated in particular areas of the spectrum. This design was adopted even though for the area of the spectrum used in the study the likelihood of confounding was not critical. Loss in articulation for the upper part of the spectrum area as compared to the lower part was not great, as reflected by the values for configurations 16 and 18 in Figure 3. Even though the pass bands were concentrated in the upper and lower parts of the spectrum, their values lie nearly on the same line as the values for the distributed configurations.

Figures 4, 5, and 6 show the intelligibility data for the 18 filter configurations plotted for each noise level. The ordinate shows percent intelligibility, the abscissa the total bandwidth of the filter configuration. The data for each noise level was fitted by a parabola of the form $Y = A + BX = CX^2$ (10). Sixteen of the 18 configurations were included in the array fitted. The data points for configurations 16 and 18 were left out because these configurations were not distributed samplings of the available spectrum. Configuration 18 included the lower 518 cycles of the spectrum and configuration 16 the upper 815 cycles.

Table 2

COMPARISON OF EXPERIMENTALLY OBTAINED INTELLIGIBILITIES
WITH THOSE COMPUTED BY USE OF THE ARTICULATION INDEX AT
THREE NOISE LEVELS AT GIVEN BANDWIDTHS

		Noise Level					
		1		2		3	
Filter Config.	Band-width	Obtained	AI Computed	Obtained	AI Computed	Obtained	AI Computed
1	1311	59	68	51	58	37	30
2	931	59	44	43	33	29	18
3	917	56	42	43	33	29	18
4	1028	57	50	49	38	35	21
5	1022	55	50	44	38	30	21
6	903	55	42	39	33	29	18
7	906	55	42	43	33	30	18
8	750	51	35	37	27	26	15
9	317	50	40	40	30	29	16
10	739	50	35	37	26	25	14
11	688	46	32	40	25	25	14
12	667	46	30	40	24	26	12
13	577	43	25	26	18	15	11
14	478	38	20	30	15	19	9
15	600	37	27	30	20	20	11
16	815	34	35	18	26	11	14
17	491	29	18	20	15	14	9
18	518	27	22	22	17	14	10

Table 3

ANALYSIS OF VARIANCE RESULTS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Between Subjects	35	14,135.0	403.8	
Within:				
Days	2	1,210.3	605.1	37.12*
Sets	2	21.6	10.8	.66
Error 1	68	1,106.1	16.3	
Periods	2	484.4	242.2	.57
Speakers	2	1,100.7	550.3	1.29
Pd x Spk	4	3,270.3	817.6	1.91
Error 2	9	3,834.2	426.0	
Filters	17	5,873.9	345.5	9.79*
Noise Levels	2	41,161.6	20,580.8	583.52*
F x N	34	738.1	21.7	.61
Days x Filters	34	1,385.5	40.8	1.16
Days x Noise Levels	4	304.2	76.1	2.16
Error 3	1728	60,955.6	35.27	
Total	1943	135,581.4		

*Significant at the .01 level.

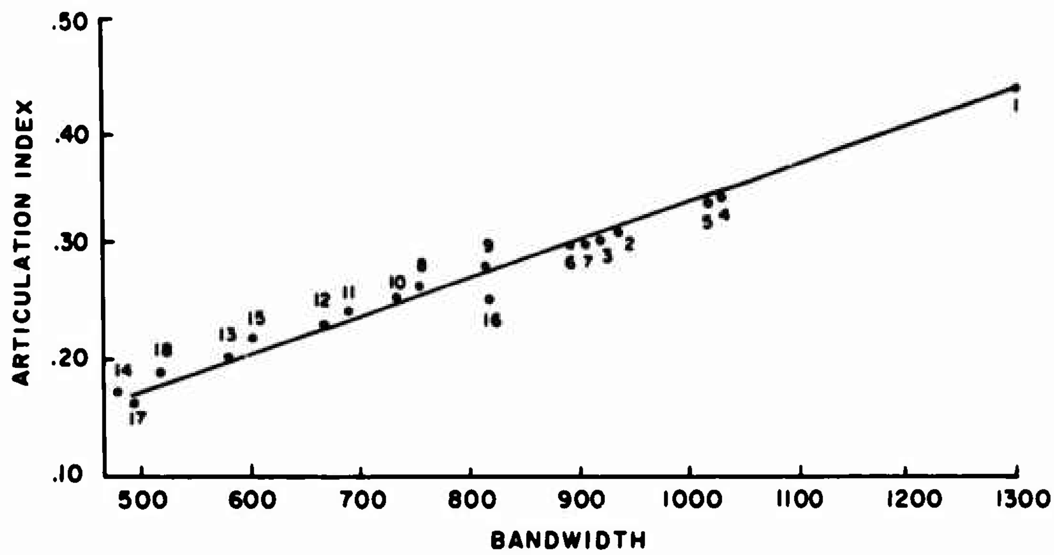

Figure 3. Relationship between Articulation Index and total bandwidth. (The numbers along the line designate filter configurations.)

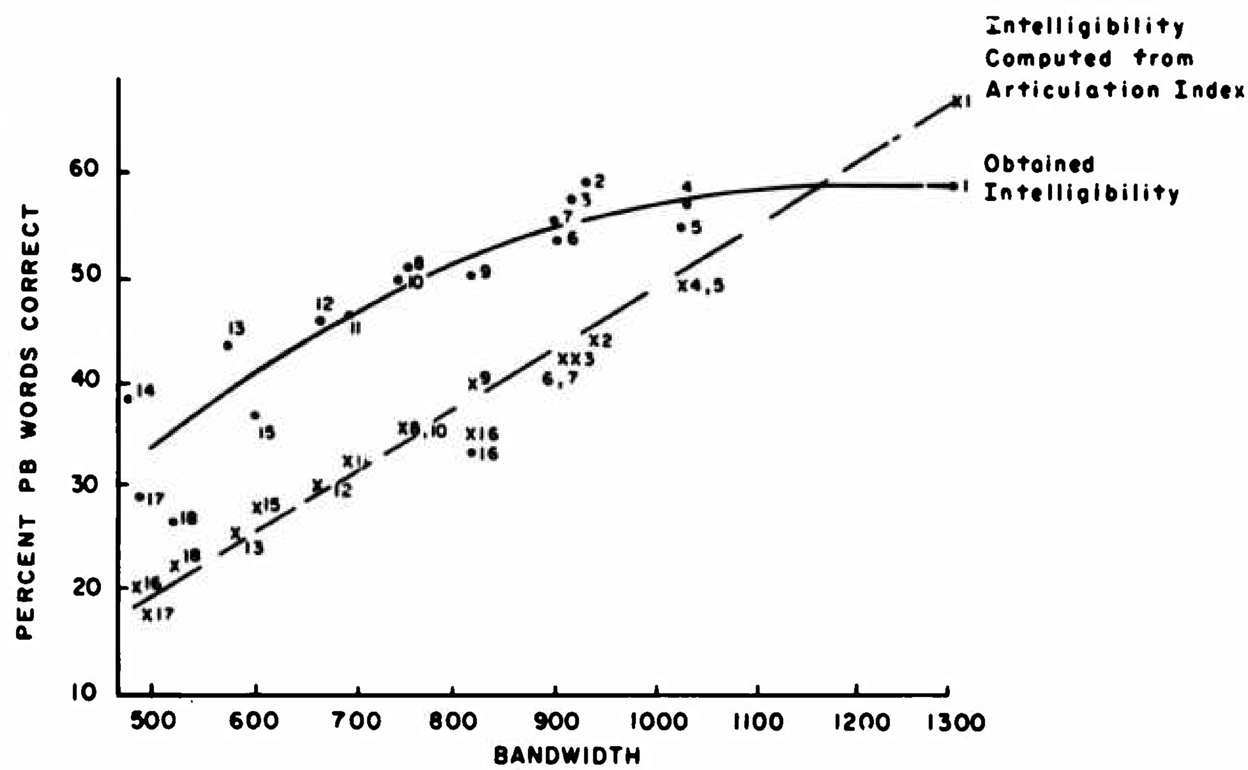

Figure 4. Intelligibility and Articulation Indexes for the 18 filter configurations under Noise Condition 1. (The figures along the lines designate filter configurations.)

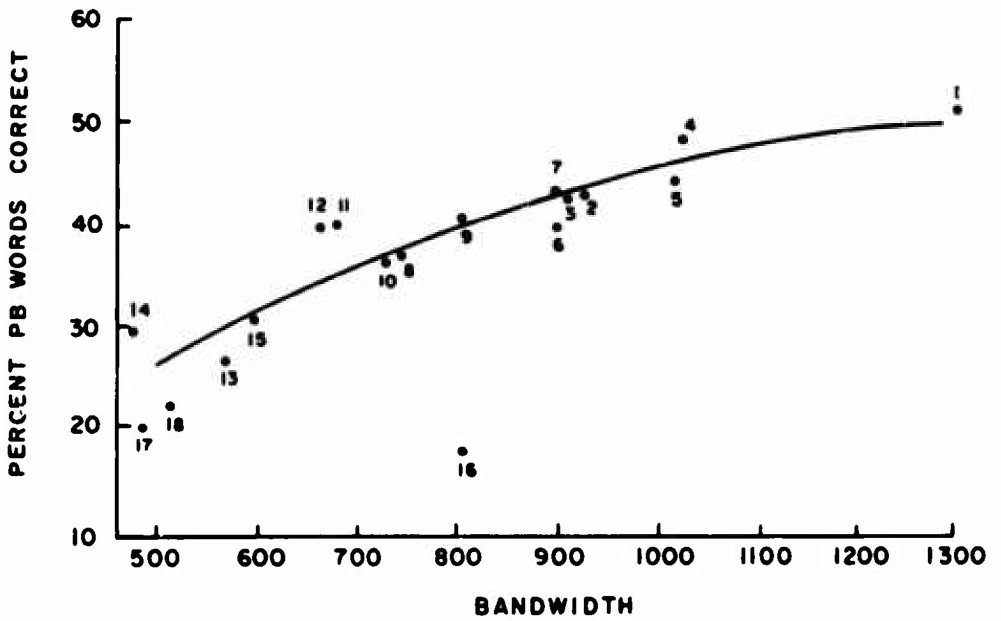

Figure 5. Obtained intelligibility for the 18 filter configurations under Noise Condition 2.

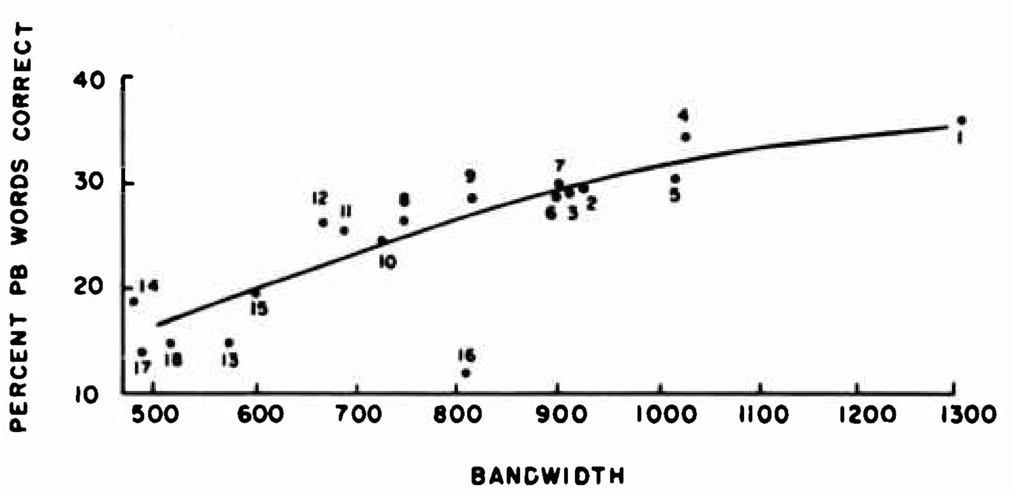

Figure 6. Obtained intelligibility for the 18 filter configurations under Noise Condition 3.

The redundancy in the speech spectrum is seen as the curvature exhibited by the data in Figures 4, 5, and 6. In Figure 4, which presents the data for the lowest noise level, intelligibility reaches a maximum of 58 percent for the full spectrum of 1300, but appears to have reached an asymptote at about 1100 cycles; even at 1000 cycles the fitted curve does not show much loss. Also, the empirically obtained values for filter configurations 2, 3, and 4 under Noise Condition 1 were not significantly lower in intelligibility than that for configuration 1 (t-tests gave probabilities between .70 and .80). Figures 5 and 6, which present the data for increased levels of noise, show progressively less curvature. The curvature component for Noise Condition 1 was significant at the .001 level. For Noise Condition 2, degree of curvilinearity was less, reaching significance only at the .05 level. The curvature for Noise Condition 3 appears slight and does not reach significance at the .05 level. From these comparisons, it appears that there is in fact an interaction between noise level and filter configuration which was not apparent from the general interaction test.

Configurations 16 and 18, examples of massed bandwidth, have an Articulation Index and bandwidth similar to those of configurations 9 and 14, in which bandwidth is distributed over the spectrum. The distributed configurations 9 and 14 produced significantly higher intelligibility than the massed configurations (Table 4). The relationship held for all three noise levels. Also, distributed configuration 4, which had a bandwidth substantially less than that of massed configuration 1, produced almost the same level of intelligibility as configuration 1 at each of the three noise levels.

Using the Articulation Index computed for each filter configuration and referring to the typical relationship between Articulation Index and intelligibility of PB words (Figure 7 in Reference 4), the expected intelligibility was computed for the filter configurations and plotted (the line of dashes in Figure 4). The values approximate a straight line. With the computed intelligibility as a reference, the experimentally obtained intelligibility values for the configurations with undistributed bandwidths (points 16 and 18) approximated what would be expected for this amount of bandwidth. The configurations with distributed bandwidths produced comparatively higher intelligibility. There seems to be no apparent reason for the discrepancy between the obtained and computed intelligibility for configuration 1.

The configurations which were the poorest--that is, the least well distributed--samplings of the spectrum (16, 17, and 18) yielded the lowest intelligibility. As shown in Figure 2, they left the largest areas of the spectrum unsampled. Configurations 16 and 18, as has been noted, were each composed of a single pass band. Configuration 17 consisted of two pass bands, one at each end of the spectrum with a gap of 820 cycles in the center.

Table 4

RESULTS OF t-TEST COMPARISONS OF SELECTION MEANS

Filter Configurations	Noise Level Condition 1	2	3
1 vs 4	.72	.59	.66
9 vs 16	5.65**	8.40**	6.66**
14 vs 17	4.09**	3.64**	1.47**
14 vs 18	4.28**	3.20**	1.24*

*Significant at the .05 level
**Significant at the .01 level

CONCLUSIONS

Segments of the speech spectrum may be excised under conditions of low noise without incurring a proportionate reduction in intelligibility. For the samplings in the study, there does not seem to be a critical size of segments excised, except for configuration 17 which left a large gap in the center of the spectrum. The other configurations were not differentially affected by size of segments excised. In Figures 3, 4, and 5, the data points for configurations with approximately equivalent bandwidths fall close together. Note the cluster formed by configurations 2, 3, 6, and 7, configurations differing in number of samples and size of segments excised. Thus, it appears that (for the spectrum used here) bands of 200 cycles or more may be excised with no greater loss than would result from excising an equivalent amount in a number of smaller segments. It appears that substantial amounts of a spectrum may be excised to eliminate bands of interference or to use the resulting interstices as channel space for other transmissions.

The effect of noise is not only to reduce the level of intelligibility but also (as may be seen by comparing the curvatures in Figures 3, 4, and 5) to change the shape of the function relating intelligibility to bandwidth. As the signal-to-noise ratio becomes less favorable, the redundancy decreases. However, speech from which segments of the spectrum have been excised appears to be just as resistant to broad-band noise as is continuous spectrum speech, as indicated by the fact that the differences in intelligibility between experimentally obtained and computed intelligibilities are of about the same magnitude for each of the noise levels.

It appears that intelligibility is not a simple function of amount of bandwidth and its position in the speech spectrum, but depends also on how the spectrum is sampled. A configuration which samples across the entire available spectrum is more efficient than one massed in a single area, even when the bandwidth is massed in the richer information bearing portion of the spectrum.

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13. ABSTRACT In controlled laboratory experimentation, the MONITOR PERFORMANCE Work Unit, USA BESRL studies the effects of factors associated with the signal, the monitoring task, the environment, and the individual in a variety of combinations. One segment of work unit effort is concerned with variables affecting the intelligibility of audio signals and speech, with present emphasis on the area of spectrum selection and binaural listening. The current publication reports on a study of the effect on the intelligibility of phonetically balanced (PB) words of excising several narrow bands from a curtailed speech spectrum (1300 cycles). A spectrum composed of several discrete pass bands was compared to (1) the total curtailed spectrum, (2) the curtailed spectrum with one large segment removed from the end, and (3) the articulation predicted by the Articulation Index. 18 PB word lists uttered at three speech-to-noise ratios constituted the stimulus material presented to 36 subjects through a filter system with selected pass bands. Results indicate that at the higher speech-to-noise ratios, eliminating several narrow bands from the spectrum does not result in a corresponding reduction in intelligibility. When the speech is 35 dB above the noise, a reduction of 20% or more can be made in bandwidth without noticeable reduction in intelligibility. As the speech-to-noise ratio is decreased, the decrement in intelligibility becomes more nearly proportional to the decrease in bandwidth. A given bandwidth distributed over a spectrum area is more effective than an equivalent bandwidth massed in one part of the spectrum. Distributed sampling of the spectrum was found to be more effective than would be expected from Articulation Index computations.

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*Binaural listening						
*Spectrum selection						
Communication channel						
Frequency bands						
Human performance						
Phonetic balance						
*Filter configurations						
Laboratory facilities						
Noise levels						
*Intelligibility values; analysis						
*Communications research						
*Military communications system						
*Articulation Index						
Signal-to-noise ratio						
Statistical methods						
Pass band system						